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Comparative study of current–voltage characteristics of Ni and Ni(Pt)-alloy silicided p^+/n diodes

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A comparative study of the $I-V$ characteristics of p^+/n diodes silicided with a pure Ni and Ni(Pt) alloy has been performed. Higher saturation currents as well as abnormal reverse $I-V$ characteristics were observed for some of the diodes which were silicided with pure Ni at 700 °C while good $I-V$ characteristics were observed for other diodes. Our results show that the forward current in the diodes with good $I-V$ characteristics is dominated by electron diffusion in the p^+ region. For diodes with higher saturation currents, it has been concluded that both forward and reverse currents in these diodes are dominated by the current following through Schottky contacts that are formed due to inadvertent penetration of NiSi spikes through the p^+ region into n region. The formation of Schottky contact was not observed in diodes silicided with a Ni(Pt) alloy, providing a clear evidence of enhanced thermal stability of Pt containing NiSi. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1374496]

NiSi is potentially an attractive silicide material due to its low resistivity, less consumption of Si, and ability to maintain low resistivity even for linewidth down to 0.1 μm.[1–3] While the thermal stability of the NiSi is the major concern for its application to deep submicron devices, it has been recently demonstrated that the addition of a small amount of foreign elements (e.g., 5% Pt) can significantly enhance the thermal stability of NiSi without increasing its resistivity.[4–6] In this work, we have measured, analyzed, and compared the $I-V$ characteristics of Ni and Ni(Pt)-alloy silicided p^+/n diodes. The results of this work reveal that, for pure Ni silicidation, an rapid thermal processing (RTP) silicidation at 700 °C or above may induce the formation of Schottky contacts in the p^+/n junctions, resulting in higher saturation currents (I_S) and abnormal reverse $I-V$ characteristics. The results also show that the formation of Schottky contact can be avoided if a small amount of Pt (5 at. %) is added into Ni, providing a clear evidence of enhancement of the thermal stability of NiSi by the addition of Pt.

p^+/n diodes were fabricated by 40 keV BF_2^+ implantation at 2×10^{15} cm^{-2} into n well in a boron doped p-type (100) silicon substrate with resistivity of 6–9 Ω cm and subsequent dopant activation annealing at 925 °C for 20 s. Pure Ni and Ni(Pt)-alloy (with 5% Pt) films, 250 Å thick, were deposited at room temperature after a dilute HF dip. The wafers were then subjected to a RTP annealing at 600 and 700 °C for 60 s in N_2 ambient for silicidation. Unreacted Ni was selectively etched off using $H_2O_2+H_2SO_4$ solution. The diodes were square shaped with an area of 1×10^{-4} cm^2 each and a dopant concentration of about 2.6×10^{17} cm^{-3} in the n region.

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Figures 1(a)–1(d) show typical $I-V$ curves measured on p^+/n diodes silicided with Ni or Ni(Pt) at 600 and 700 °C. The ideality factors and saturation currents are extracted from the forward $I-V$ curves in Figs. 1(a)–1(d) and shown in Fig. 2. As shown in these figures, good $I-V$ characteristics are observable for the majority of measured diodes except some of the diodes which were silicided with pure Ni at 700 °C. The ideality factors and saturation currents of the diodes with good $I-V$ characteristics are in the range of 1.01–1.08 and 2×10^{-15}–9×10^{-15} A, respectively. For the diodes with poor $I-V$ characteristics, the corresponding ranges are 1.11–1.13 and 5×10^{-14}–3×10^{-13} Å. In addition to higher saturation currents, these diodes also exhibit abnormal reverse $I-V$ characteristics, i.e., drastically increased leakage current with increasing reverse bias.

It is well known that ideality factor is close to 1 when the forward current is dominated by diffusion current and becomes close to 2 in the presence of dominant recombination current. For the diodes with good $I-V$ characteristics, it is therefore believed that the forward current is dominated by the diffusion current. Assuming that no Schottky contacts are formed in these diodes, the saturation currents can be expressed as

$$I_S = AqD_p p_{no}/L_p + AqD_n n_{po}/W_{P+}, \tag{1}$$

where A is the diode junction area, q is the electron charge, $D_{p,n}$ are hole/electron diffusion coefficients, p_{no} and n_{po} are equilibrium hole/electron concentrations in n/p^+ regions, L_p is the hole diffusion length given by $(D_p\tau_p)^{1/2}$ with τ_p as the hole lifetime in n region, and W_{P+} is the width of p^+ neutral region. Using Eq. (1), the L_p and W_{P+} values are calculated assuming either hole or electron diffusion being dominant diffusion current. In the case of hole diffusion in n region

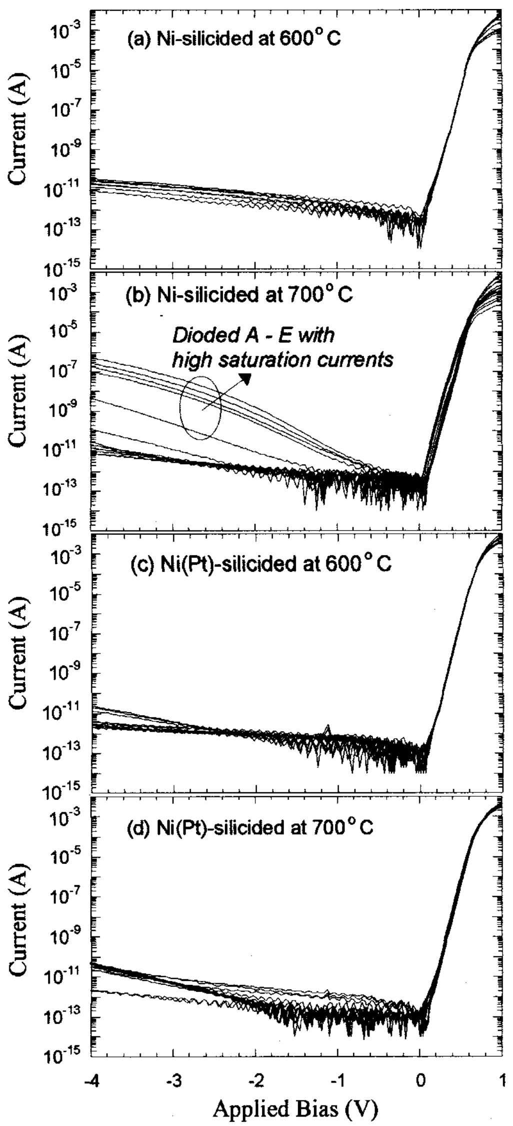

FIG. 1. Typical $I-V$ curves measured on p^+/n diodes silicided with Ni and Ni(Pt) alloy films at 600 and 700 °C. Ni(Pt) silicided p^+/n diodes show tight distribution of series resistances.

being the dominant diffusion current, we obtain $L_p \sim 1 \times 10^{-5}$ cm for a typical I_S value of 5×10^{-15} A, setting τ_p around 2.5×10^{-11} s. This is an extremely low value for minority carrier lifetimes in Si, considering that normal minority carrier lifetime in device quality Si is in the range of a few microseconds to a few hundreds microseconds. On the other hand, in the case of electron diffusion being the dominant diffusion current, we obtain a value of a few hundred angstroms for W_{P+},[7] which is close to the thickness (~700 Å) of p^+ region. Therefore, it seems that the forward diffusion current in these diodes is dominated by electron diffusion in the p^+ neutral region.

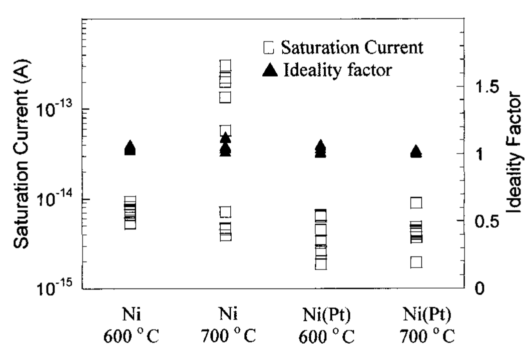

FIG. 2. Distribution of saturation currents and ideality factors obtained from forward $I-V$ curves in Fig. 1. Higher saturation currents as well as abnormal reverse $I-V$ characteristics are observable for some of diodes (labeled A–E) which were silicided with pure Ni at 700 °C.

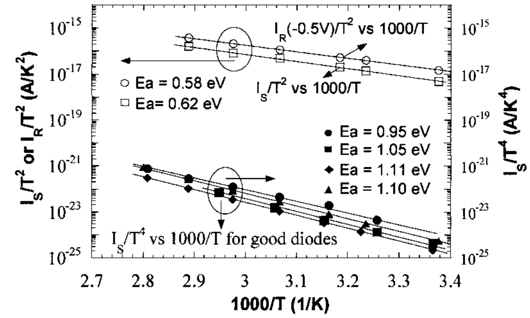

FIG. 3. I_S/T^2 vs 1000/T and $I_R(-00.5\ V)/T^2$ vs 1000/T curves of the diode which was silicided with pure Ni at 700 °C and shows highest saturation as well as reverse leakage current. I_S/T^4 vs 1000/T curves of the diodes with good $I-V$ characteristics are also plotted to show that current transport in these diode is dominated by diffusion mechanism (see Ref. 9).

For the diodes with higher saturation currents, it is tempting to attribute the observed higher saturation current and slightly higher ideality factor to the possible presence of an appreciable recombination current. However, this possibility is ruled out due to following two reasons. First, though slightly higher, the ideality factors (1.12–1.13) of these diodes are still close to 2, but much lower than 2. Second, the ideality factor remains constant for forward bias up to the point where the series resistance effect becomes significant. For a diode with an appreciable recombination current, its forward $I-V$ curve normally features two distinguishable ideality factors, a value considerably larger than 1 in the lower voltage region and a value close to 1 in the higher voltage region. Therefore, the observation of a constant ideality factor suggests that recombination currents are not the dominant current sources under forward bias in these diodes.

The observed behavior of the forward current in the diodes with poor $I-V$ characteristics is analyzed in this paper from the viewpoint of Schottky contact being formed by inadvertent penetration of NiSi through the p^+ region into the n region. This is based on the analyses of the Arrhenius plots for the saturation and leakage currents (Fig. 3). As shown in Fig. 3, the measured activation energies associated with the saturation current and reverse leakage current I_R (at -0.5 V) for the diode with the highest saturation current are 0.62 and 0.58 eV, respectively. Assuming that these values are effective barrier heights of a Schottky barrier under different biases (i.e., 0 and -0.5 V), one obtains a value of 0.67–0.64 eV for the ideal barrier height ϕ_{Bn}, taking into account the lowering of the barrier height by the image force. The ϕ_{Bn} value obtained (0.67–0.64 eV) is much smaller than Si band gap (1.12 eV), but very close to the barrier height of NiSi/n-Si (0.65 eV).[8] This good agreement seems to provide a clear evidence that Schottky contacts are formed in the diodes with poor $I-V$ characteristics, and the forward currents in these diodes are dominated by the currents flowing through the Schottky contact areas. The effective Schottky

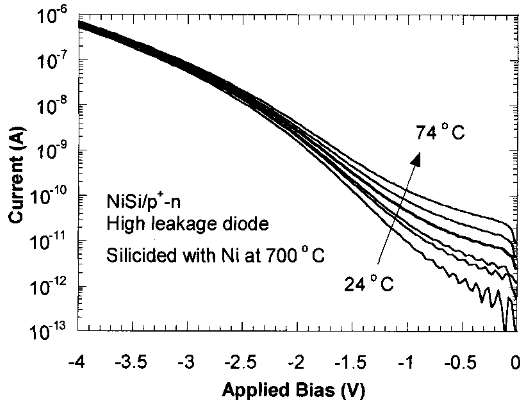

FIG. 4. Temperature dependence of reverse $I-V$ characteristics of the diode with highest saturation and leakage currents. The diode was silicided with pure Ni at 700 °C.

contact areas extracted using the measured saturation currents and the effective barrier height (0.62 eV) under zero bias are found to be less than 0.001% of the junction area of 1×10^{-4} cm^2 (i.e., 0.066 μm^2 for the diode with the highest saturation current). In Fig. 3, one can also see that the saturation current activation energies (0.95–1.11 eV) of the diodes with good $I-V$ characteristics, obtained from I_S/T^4 vs $1000/T$ curves,[9] are close to the Si band gap (1.12 eV). This result further confirms our previous conclusion that the electron diffusion current dominates forward currents in these diodes.

In view of the earlier correlation of the observed higher saturation current with the presence of Schottky contacts, the observation of abnormal reverse $I-V$ behavior in the diodes with poor $I-V$ characteristics can be understood if the dominant reverse current under higher reverse bias is attributed to the tunneling currents through the Schottky barriers. The reasons for this conclusion are as follows. First, with I_R as reverse leakage current, T as temperature, E as maximum electric field, and ϵ as permittivity, the measured slopes of I_R/T^2 vs $E^{1/2}$ curves (0.020–0.075 V$^{1/2}$/cm$^{1/2}$) are much larger than the theoretical value 0.0044 V$^{1/2}$/cm$^{1/2}$ (at 24 °C), as calculated taking into account the lowering of the Schottky barrier height by the image force, which is given by $\Delta\phi=(qE/4\pi\epsilon)^{1/2}$. Thus, the observed rapid increase in the reverse current with increasing reverse bias cannot be explained just on the basis of the lowering of the effective barrier height by the image force. On the other hand, the effect of temperature on the reverse $I-V$ curves, as shown in Fig. 4, reveals nearly athermal behavior for biases of few volts, which is considered a fingerprint of tunneling current.

The formation of small area Schottky contacts in Ti silicided n^+/p diodes was also reported by Ada-Hanifi *et al.*[10] They explained the observation of dominant tunneling currents in the same diodes in terms of the enhancement of the local electric fields (1–3 MV/cm) near the silicide spikes (200–600 Å radii). According to the criteria given by Padovani and Stratton,[11] it can be shown that almost the same values (>1 MV/cm) of maximum electric field are required for tunneling current to be the dominant reverse current at room temperature in a NiSi/*n*-Si Schottky barrier. Such fields are very large and cannot be reached uniformly in our devices, given the doping concentration in *n* regions (2.6×10^{17} cm^{-3}). Following the analyses of Ada-Hanifi *et al.* it is thus proposed that the high electric field results from the enhancement of local electric fields near individual NiSi silicide spikes that constitute the total effective Schottky areas, as calculated from the measured saturation currents (e.g., 0.066 μm^2 for the diode with the highest saturation current).

In summary, we have measured, analyzed, and compared the $I-V$ characteristics of p^+/n diodes silicided with a pure Ni and Ni(Pt) alloy. Good $I-V$ characteristics were observed for all the diodes except some of the diodes Ni-silicided at 700 °C, which showed higher saturation currents as well as abnormal reverse $I-V$ characteristics. Experimental results show that electron diffusion current in p^+ region dominates the forward current in the diodes with good $I-V$ characteristics. In contrast, for diodes with poor $I-V$ characteristics, it has been concluded that both forward and reverse currents are dominated by the current that flows through Schottky contacts which are inadvertently created as a result of NiSi spikes penetrating through the p^+ region in the *n* region. For diodes silicided with a Ni(Pt) alloy, all showed good $I-V$ characteristics without any evidence of the formation of Schottky contacts. This provides a clear evidence of enhancement of the thermal stability of NiSi due to the addition of Pt.

[1] T. Ohguro, S. Nakajima, M. Koike, T. Morimoto, A. Nishiyama, Y. Ushiku, T. Yoshitomi, M. Ono, M. Saito, and H. Iwai, IEEE Trans. Electron Devices **42**, 2305 (1994).
[2] F. Deng, R. A. Johnson, P. M. Asbeck, S. S. Lau, W. B. Dubbleday, T. Hsiao, and J. Woo, J. Appl. Phys. **81**, 8047 (1997).
[3] R. Mukai, S. Ozawa, and H. Yagi, Thin Solid Films **270**, 567 (1995).
[4] D. Mangelinck, J. Y. Dai, S. K. Lahiri, C. S. Ho, K. L. Pey, and T. Osipowicz, MRS Spring Meeting, San Francisco (1999).
[5] D. Mangelinck, J. Y. Dai, J. S. Pan, and S. K. Lahiri, Appl. Phys. Lett. **75**, 1736 (1999).
[6] T. Ohguro, S. Nakamura, E. Morifuji, M. Ono, T. Yoshitomi, M. Saito, H. S. Momose, and H. Iwai, Tech. Dig. Int. Electron Devices Meet. **1995**, 453 (1995).
[7] Assuming that the boron concentration N_a at the edge of p^+ space charge region is about 3×10^8 cm^{-3} and the effective electron diffusion coefficient D_n in neutral p^+ region is about 3 cm^2/s, one obtains $W_p^+\sim670$ Å.
[8] M. Liehr, P. E. Schmid, F. K. Le Cones, and P. S. Ho, Phys. Rev. Lett. **54**, 2139 (1985).
[9] The saturation current I_S is given by $I_S=AqD_nn_{po}/W_{P+}$ in good diodes with $D_n\propto T\mu_n$ and $n_{po}\propto T^3\exp(-E_g/KT)$. For high dopant concentration N_a ($10^{18}-10^{19}$ cm^{-3}), the electron mobility μ_n is almost independent of temperature in the neighborhood of 300 °K (see Ref. 12), therefore $I_s\propto T^4\exp(-E_g/KT)$ with E_g as band gap and K as Boltzmann contant.
[10] M. Ada-Hanifi, A. Chantre, D. Levy, J. P. Gonchond, Ph. Delpech, and A. Nouaihat, Appl. Phys. Lett. **58**, 1280 (1991).
[11] F. A. Padovani and R. Stratton, Solid-State Electron. **9**, 695 (1966).
[12] *Quick Reference Manual for Semiconductor Engineers*, edited by W. F. Beadle, J. C. C. Tsai, and R. D. Plummer (Wiley, New York, 1985).